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Moletronics: Transforming Nanotechnology and Nanocomputers from Vision to Reality

I am Kwan Kwok, manager of DARPA's Molecular Electronics Program, an innovative program often referred to as "Moletronics." It is a privilege to speak to you today here at DARPATech 2002. Because of its theme—Transforming Fantasy to Reality—this symposium is a natural forum in which to discuss Moletronics, a research and development program that is transforming the dream of nanotechnology and nanocomputing to reality.

Building a molecular electronic computer in the Moletronics Program automatically projects us into the truly small, small world of nanotechnology and nanocomputing. One nanometer is 1 billionth of a meter, about 10 atomic diameters. Thus, the nanometer scale is the scale of individual molecules. Nanotechnology involves utilizing the properties of these incomprehensibly small, molecular-scale structures and controlling the organization of matter on this very smallest of scales. Similarly, nanocomputers are ultradense computers built from nanometer-scale or molecular-scale components and integrated or organized on this same scale.

For at least 40 years, visionaries—starting with the great Richard Feynman—have only dreamed of nanocomputers. However, the tightly focused team of outstanding scientists and engineers put together by DARPA in the Moletronics Program is actually building a futuristic molecular electronic nanocomputer. By the autumn of 2004, we will actually operate a molecular electronic memory, which is the most basic building block for an electronic nanocomputer. Furthermore, in the process of inducing this revolutionary change in the quantitative and the qualitative nature of computing, we also are creating a revolution in materials. We are realizing the dream of artificially self-assembled, nanostructured materials.

I am able to tell you about these developments with confidence today because the DARPA Moletronics Program has a pragmatic, systematic plan for producing these revolutionary changes in the technological infrastructure of the United States.

The plan consists of four steps:

1. Building and operating molecular electronic devices

2. Using them to build and operate molecular circuits

3. Refining next-generation methods for fabrication using chemical self assembly

4. "Self-assembling" molecular devices and molecular circuits into an entire computer architecture integrated on the molecular scale

Of course, as simple as it is to relate these steps, this is a very challenging plan. I am happy to report, however, that my colleagues and I are succeeding in implementing the plan, transforming nanotechnology and nanocomputers from fantasy to reality.

As the first step in implementing our plan, we have demonstrated and refined molecular-scale electronic devices: molecular-scale switches and wires. We have discovered that each of these small molecules, which are only a few nanometers long, can conduct as many as 1 trillion electrons per second. This provides a current density as much as 1 million times as great as an ordinary copper wire.

Also, these tiny molecules can switch such electric currents. An example of this kind of molecule is the 3-nanometer-long molecular structure shown in the upper left of the image displayed on the screen. As shown in the graph on the lower right, when we change the voltage applied to this molecule, it first conducts almost no current. The molecular switch is "off." But then, as the voltage increases, the current that can pass through the molecule increases dramatically to the peak shown in the graph. The molecular switch is "on." This switch was invented, fabricated, and demonstrated by my colleagues at Rice University and Yale University. It is a very useful device, as I will discuss in just a minute.

Another Moletronics research collaboration between Hewlett-Packard Corporation and UCLA has invented and demonstrated a different type of useful switching molecule. As shown in the graphic that you see displayed now, this molecule consist of two interconnected rings. When the molecule switches, it undergoes a structural change as the two rings rotate relative to each other. This constitutes a nanometer-scale mechanical switch.

As part of the second step in our plan, we have learned how to build and operate computer memory circuits assembled from the molecular-scale parts just described. As shown in the upper left of the displayed graphic, molecular switches developed at Rice and Yale, much like the one I just showed you a minute ago, have been used to build and operate a memory cell. As shown on the lower right, bits of information can be written to and read from this molecular memory cell just like the ones in your desktop or laptop computers.

Unlike conventional memories, however, the molecular memory cells retain their information for a long time, even when the power is turned off. Thus, these cells do not require the frequent "refresh" that present-day microelectronic memories do. For this reason, molecular electronic memory should use much less electrical power.

In the third and fourth steps of our molecular electronics development plan, we devised architectures and methods for the hierarchical self-assembly of extended electronic systems of nanometer-scale components. Furthermore, we are just now beginning to assemble computers according to these extended architectures.

One such architecture is formed by crossbars that sandwich molecular switches like those just shown between two perpendicular layers of nanometer-scale wires or nanowires. The architecture is reminiscent of the ferrite core memory structures used in the early days of computer development, but these structures are many orders of magnitude smaller. A sketch of this architectural plan is shown on the upper left of the image on the display. In the picture on the lower right, you can see a scanning electron micrograph of this vision transformed to reality—a prototype of our nanocomputer memory realized by Hewlett-Packard and UCLA.

On the next viewgraph is a more radical prototype nanocomputer architecture being realized by the Rice-Yale University team. At the top of the graphic is a vision of an interconnected, ultra-high-density network of molecular wires and switches. At the bottom, this vision is transformed to reality.

A particularly important virtue of this prototype approach is that it is very fast and inexpensive to build. Instead of sophisticated and very costly fabrication equipment, this approach requires sophisticated, but relatively inexpensive, software to sort out the connectivity of the molecular network that makes this type of nanocomputer operate. That software is being developed in this program and will reach a major milestone this summer.

The examples I have just shown you are only a few of the remarkable innovations toward nanocomputers that have been developed and demonstrated by the investigators in the DARPA Moletronics Program. They illustrate that the 40-year-old dream of nanotechnology and nanocomputers is about to be realized by DARPA. We are harnessing the electrical properties of individual molecules and we are learning to put very, very large numbers of molecules where we want them in order to build a next-generation nanocomputer.

There are several reasons why these impending transformations from microtechnology to nanotechnology and from microcomputers to nanocomputers are so important. The first is that they are essential for preserving the vitality of the information technology industry that is so critical to our national defense.

To continually deliver more performance in our present-day computers, industry has succeeded in shrinking conventional microelectronic computer circuitry exponentially rapidly to fulfill the expectations of Moore's Law. This has been a remarkable achievement, but conventional electronics technology is rapidly approaching the physical limits of miniaturization at an exponential rate.

Also, the continued miniaturization of microelectronics has become more and more costly for industry, reducing its ability to be truly innovative and responsive. Simply stated, this is because carving up a silicon chip into a trillion nanometer-scale pieces, as the electronics industry is attempting to do, is a very difficult and expensive approach to further miniaturization.

In contrast, the nanotechnology of molecular electronics has a number of natural advantages that promise to transcend these difficulties. This is because molecules are natural nanometer-scale structures that can be made by the trillions very inexpensively in a beaker or test tube.

Further, we have shown in the DARPA Moletronics Program that natural molecular-scale structures can deliver electrical performance comparable to—and, in some cases, superior to —bulk, solid-state silicon. Even more remarkable, we are learning to harness the natural flexibility and diverse chemistry of molecules to coax them to self-assemble themselves into extended computational systems. This will enable us to increase dramatically the density and performance of computation over the next few years. The prototype nanocomputer memory that the Moletronics Program produces in 2004 will have an effective density of a hundred billion bits per square centimeter. This nanocomputer system, as planned in the industry's roadmap, will have components that are 10 thousand times smaller and at least 100 times as dense as the conventional microcomputers of 2004. DARPA's molecular electronic memory should lead to a large increase in data storage capacity at a greatly reduced cost.

Needless to say, this achievement will have dramatic benefits for U.S. national defense and for our industries. Our successes thus far have stimulated much wider and still growing industrial interest in nanotechnology and molecular electronics.

An even more important impact will be a qualitative transformation of the nature of computing. This could be an even greater transformation than the one in which microcomputers replaced mainframes during the 1980s. In the forthcoming nanocomputer revolution led by DARPA, computers will become small enough to be placed on top of a human cell. Computation will literally become a property of matter.

Even beyond these radical advances in the quantitative and qualitative nature of computation, Moletronics is stimulating a revolution in materials. To compute with molecular-scale structures, we have found that we must learn how to characterize and organize them on similar scales, one by one, and in vast arrays. This is creating a whole new science and industry of "nanostructured materials."

But the most important impact of our efforts in the DARPA Moletronics Program possibly will be seen in generations to come. The nanocomputers and the nanomaterials developed by our moletronics investigators will stimulate a new wave of innovation as our children and their children begin to assimilate these revolutionary changes and harness them with their own imaginations.

In summary, my collaborators and I in the DARPA Moletronics Program are working on realizing the dream of nanotechnology successfully executing a systematic plan to transform the vision of molecular electronic nanocomputers to reality. We will deliver a prototype ultradense memory in September 2004 using molecular-scale components and we hope (and expect) this important development will seed a revolution in materials as well as in computation.

Thank you